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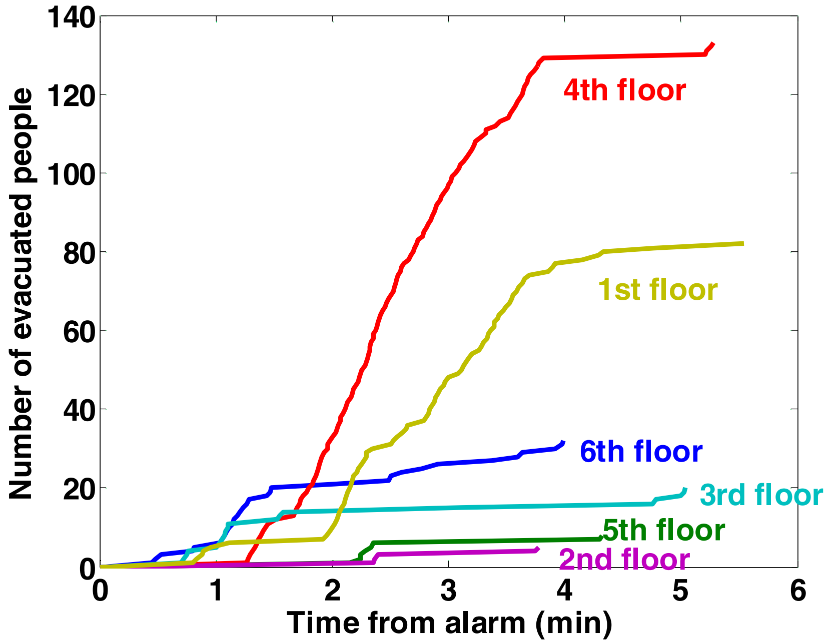

Evacuation experiments in offices and public buildings

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Title

Experimental observations of evacuation situations

Abstract

In fire safety engineering, the performance based design concept relies strongly on the use of computer simulations of fire and evacuation processes. The validation of the simulation tools requires experimental information on the human behaviour during the evacuation situations. In this work, two different types of evacuation situations were studied. The first type was evacuation drills which are normally carried out as part of the safety training of the staff in public buildings and workplaces. The advantage of evacuation drills is that the building (and, if necessary, also the occupants) can be equipped with monitoring devices in order to observe the events during the evacuation. The drawback of the evacuation drills is that the building occupants are normally informed beforehand which may affect the decision making processes. The second type was actual evacuations which occur every now and then. The advantage of actual evacuations is that the decision making processes are likely to be similar to what they would be in case of a real fire.

The main techniques used for the observation of evacuation drills were video cameras and Radio Frequency Identification (RFID). Both techniques were used in the evacuation drills in a public library and two office buildings. A large amount of information was obtained and the problems in the application of the observation techniques were identified. In particular, the results show that when the RFID technique is used, the placement of the antennas and tags is very important. With careful placement of the antennas and tags, the reliability of the RFID technique as applied in the current work may be sufficient for scientific purposes. The reliability is poor if the tags are placed under the clothing of other absorbing material.

In the observation of an actual evacuation of a large shopping centre, the recordings of the surveillance cameras were used to measure the flow rates of people. The results are very promising and indicate that the collection of surveillance camera recordings from large evacuations should be started.

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Preface

The reported work was conducted in the project "Improvement of the evacuation safety of large buildings by combined simulation of fire and evacuation processes" within the Modelling and Simulation Technology Programme (MASI) of the Finnish Funding Agency for Technology and Innovation (Tekes). The purpose of the experimental work was to provide validation data for the FDS+Evac software developed at VTT. The research project was funded by Tekes, the Finnish Fire Protection Fund, the Ministry of the Environment, the Finnish Academy and VTT.

The support from the safety organizations of the target institutions was essential for the successful implementation of the experiments, and greatly acknowledged. The contribution of Invisian Oy during the library evacuation is also greatly appreciated.

Ms. Katri Matikainen made the observations on the human behaviour aspects during the public library evacuation. The following VTT researchers participated in the conduction of the experiments by making observations and using video cameras: Pekka Pursula, Konsta Taimisalo, Mari Niemelä, Kaisa Belloni, Kati Tillander, Esko Mikkola, Tuuli Oksanen and Johan Mangs. The technical challenges in the placement of video cameras during the office evacuations were proficiently solved by Mr. Arto Hätelä of VTT.

Contents

1. Introduction

New public buildings typically integrate many different functions like work places, shops, restaurants and recreational activities under the same roof. These buildings have become a new type of public 'living rooms'. At the same time, people spend more and more time outside the work and home, at least partly due the increasing portion of single person households. As a result, the fraction of the time the people spend in buildings with at least hundreds and possibly thousands of other people is increasing. This, in turn, increases the probability of fires or other events requiring evacuation of thousands of people.

Traditionally, the design of evacuation capacity is based on the simple design criteria on the required width and length of evacuation routes. These criteria are based mainly on experimental findings and lessons learned from the past hazards. However, it would not be possible to build the large multi-purpose centres using the simple design rules. Instead, these places are usually designed using the performance based design method, in which the safety of the design is studied from the viewpoint of the entire system, not as fulfilment of individual rules given by the building code. The performance based design relies strongly on the numerical modelling and simulation of both the fire and evacuation processes. FDS+Evac is one of the few software tools where the fire and evacuation simulations can be fully coupled together. The objectives of the FDS+Evac development are the capability to simulate large crowds and the realistic interaction between the evacuation and fire processes. FDS+Evac is based on the human movement model of Helbing *et al.* [1995, 2000, 2002] combined with the Fire Dynamics Simulator [McGrattan *et al*. 2007] and some new types of models for the socio-psychological effects and the evacuee decision making processes.

For the reliability of the performance based design, the simulation tools must be validated for the given type of application. In validation work, the computational results are usually compared against experimental results. Accurate and well documented measurements are needed in order to draw a good picture on the model strengths and weaknesses. Usually the primary technique of observations in evacuation experiments is video recording. The quantitative measurements from the video recordings are then made manually as a post-processing. The validation of decision making processes introduces a new challenge for the experimental design and measurements since quantitative techniques to observe human decisions, like the selection of escape routes, are not readily available. New techniques that can identify and monitor the location and movement of individuals are thus needed. One such a technique is the Radio Frequency Identification (RFID), commonly used for remote identification of people and items. Performing real scale evacuations with many video cameras and observers is very labour intensive. Adding the new techniques is likely to increase the cost of the experiments, at least in the beginning when a lot of the work is made manually. The purpose of the current work is to provide validation data for some aspects of the evacuation modelling and to study the applicability of RFID on monitoring evacuees in field scale evacuation experiments.

Several difficulties are associated with performing field experiments on public spaces like shopping centres: The initial conditions can not be presumed accurately and the measurements are difficult to perform without considerably affecting the awareness of the people. The most important difficulty is the reluctance of the property owners and administrators to organize the evacuation tests. Usually the experiments are conducted in conjunction with the evacuation training program and in co-operation with the local safety organizations. Fully blind evacuation exercises, where the people are given an impression of a real fire, are usually considered useless for training purposes and harmful for the business. On the other hand, both real fires and false alarms take place every now and then requiring the evacuation of the building. Valuable information could be gathered if these events could be monitored. Many buildings and public spaces are equipped with surveillance cameras that record the events and store them for a certain period of time. Typically, this period is from few days to a month. One goal of the current work is to find out the practical issues related to the utilization of surveillance cameras as a source of evacuation data.

2. Experimental methods

2.1 Video imaging

Video imaging may be used for two primary objectives in evacuation experiments: It may provide a recording of the door or exit flow for later use, or it may provide information on the reaction and premovement times, decision making processes and other human behaviour aspects for later analysis. The consumer level digital video (DV) cameras have become very popular during the last few years. As a result, the camera prices have come down to a level that enables the purchase of several such cameras for an experimental evacuation project. The image quality of even the smallest DV cameras with approximately one million pixels[1] is sufficient for making observations on evacuations.

The main difficulty of using the video cameras is related to the placement of cameras. This is especially true for indoor situations when the camera must be used without an operator. Custom made stands and supports must be used.

When used as a recording of an exit flow, a proper technique is needed for counting the humans. The resulting data should contain the cumulative sum of evacuees at sufficient time resolution to enable the computation of flow rates. In this work, the flows were counted manually by using a custom made computer program, *Evaccounter*, that stores the times when the user presses the keyboard while watching the video. The software gives the exact times of key-presses and can scale the times based on the specified starting and ending times for low-speed video playback. The user interface of the counter software is shown in Figure 1. The software was developed using MATLAB.

Automatic detection of moving objects in video material is used in the security and surveillance camera applications. The application of such techniques was studied by contacting companies selling the services of human detection. Based on the survey, the best accuracy can be achieved if the cameras are placed directly above the observed area. Some of the surveillance systems have utilities that allow drawing a virtual line in the picture, and automatically keeping track of people crossing the line. However, the placement directly above the observed area is very difficult in practical evacuation experiments on the field. Also, some of the commercial systems worked only in on-line mode providing no possibility for post-processing.

[1] Situation in 2006.

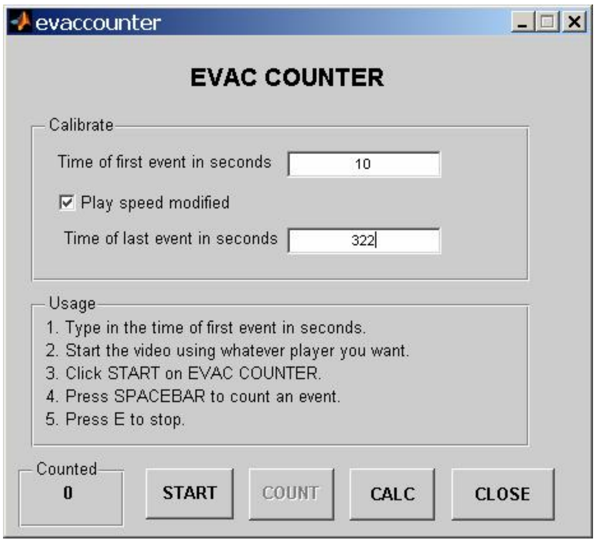

Figure 1. The graphical user interface of Evaccounter MATLAB program.

2.2 Radio Frequency Identification (RFID)

2.2.1 Remote person identification

One goal the project was to study the individual level person identification in a non-contact manner without the need for mechanical, acoustical or optical devices. All latter mentioned techniques require mechanical structures assembled in the passage of test persons and usually do not offer the possibility for individual identification but only for simple counting of the number of individuals. They are also very vulnerable because of the big variation in the size and manner of movement of people in different surroundings. Accuracy of most optical devices suffers from smoke, water vapour and loss of sight which also holds true for acoustical devices. In real fire evacuation situations and also in rehearsals, no mechanical devices in the passage of people are allowed. This restricts the available identification methods.

In recent years, radio frequency identification (RFID) methods for item management have developed rapidly. The frequencies used in these circumstances extend from 135 kHz to 2.45 GHz. The applications can be divided to proximity, vicinity and remote sensing applications depending on the frequency. Frequency range from 433 MHz to 2.45 GHz and above is considered to be the remote sensing range.

The boundary between vicinity and remote sensing is a little bit faltering. Usually 13.56 MHz is regarded as a vicinity frequency because it requires large port-type antennas for the reader devices in order to obtain a reading distance of 1 meter. The link between the reader device and the object to be read, the tag, is realised with inductive near field coupling. Anything below 13.56 MHz is considered proximity or close coupled sensing.

The techniques used in item management can easily be transferred into person identification. Most promising frequency ranges are the 869 MHz (ultra high frequency, UHF) and 2.5 GHz frequencies. In these frequencies, the size of antennas and tags is less than 30 cm. Size of most tags is of the order of a few centimetres. The UHF frequency band is at the moment the most popular one and a multitude of both tags and readers exist there. This is one of the reasons why UHF tags and readers were chosen for this project.

2.2.2 RFID-Techniques at the UHF Band

Both active and passive tags are available in the UHF-band. Active tags include a battery or other source of energy and are bigger and heavier than passive tags. Passive tags consist only of an antenna structure and a small (~ 1 mm x 1 mm) silicon chip. The antenna structure can be manufactured on a plastic sheet or board and the chip is glued or bonded on it. Passive tags receive the energy they need wirelessly from the reader device during the reading operation.

There are several European and American standards which regulate the power and modulation techniques, which can be used at a certain frequency band. The ISO/IEC FCD 18000 Radio-frequency Identification Standard for Item Management Communications below 135 kHz and at 13.56 MHz, 433MHz, 860–930MHz and 2.45GHz is the newest European standard.

In the USA, Electronic Product Code (EPC) standards have existed longer than in Europe and partly because of this fact EPC-tags are at the moment more popular than tags with ISO standards. The ISO 18000 standard tries to bring the European and American techniques closer to each other. Because of the popularity and a Finnish manufacturer, Raflatac Oy (formerly Rafsec), passive EPC-tags were chosen for this project.

The Raflatac G2 Short Dipole Wet Inlay, Global UHF C1G2 EPC (3000843) tag and the size of it are illustrated in Figure 2. Tags were inserted in an ID badge in order to keep them apart from the body. In UHF frequencies the electromagnetic field does not penetrate into the human body or other electrically conducting substances very much. This will “kill” the electromagnetic field and prevent the reading operation at the surface of the body.

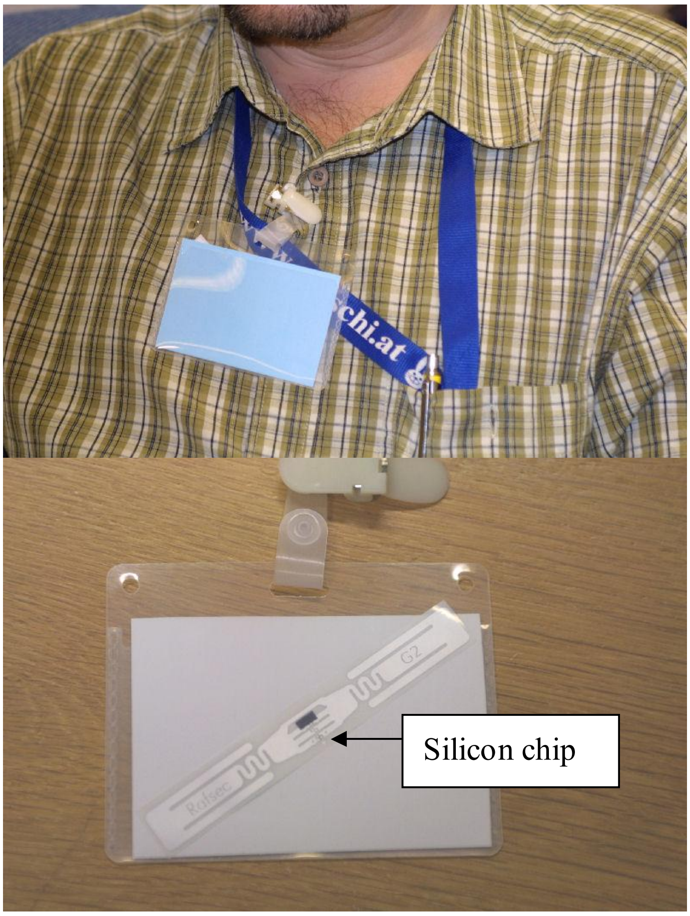

Figure 2. The Raflatac (formerly Rafsec) EPC Gen2 RFID-tag in an ID badge. The silicon chip is visible in the lowest middle part of the tag just above the plus sign.

There are, however, tags which are especially designed on electrically conducting surfaces but they are much more expensive, stiffer and thicker than the flexible sticker type tags chosen for this project. The cost of Raflatac tags is approximately 50 cents per piece in small quantities. They can be integrated into plastic ID badges. Every tag has a unique identification number which can be chosen by the user. The UID is 96 bits long and thus gives 2^{96} different combinations. This yields to more than 10^{27} choices for the identification number.

When interpreting the results one has to bear in mind that the actual number of tags which was delivered to the test persons is not necessarily the amount which was participating to the tests. Also, the correct attachment as described in the instructions is presumably not the way people used the tags. There was no means of controlling the use of tags during the evacuations or checking the actual placement of the tag immediately afterwards. The tags were not delivered or collected personally by VTT staff. It is also impossible to check the exact amount of tags from video tapes.

The UHF-readers chosen for this project are the FEIG ID ISC LRU 1000 and the Deister UDL 500. The FEIG reader has four external passive antennas while the Deister reader only has one internal antenna. Due to the fact that the FEIG reader antennas are passive, the maximum cable length from one antenna to the reader is limited to less than 10 meters, if a reading distance of 2 to 3 meters from the antenna is desired. Shorter cables give larger reading distance because the signal is not attenuated as much as in longer cables.

The FEIG reader can be controlled through serial bus, ethernet or WLAN. The Deister reader is controlled via an RS485 interface. As in this project, the FEIG reader is also able to act as a data logger, which has a memory of approximately 3000 readings. The Deister reader has to be controlled and read on-line. Both readers may be set to a mode which only allows one tag to be read once in a certain period, which can be set to a maximum value of 10 minutes. This will reduce the memory requirements and the minimum speed of the controlling interface.

The reading distance of a tag depends on the quality of the tag, the power available and the surroundings. Typically it varies from 2 meters to 4 meters. Nowadays, however, even 8 meter reading distances are quite common with good quality tags and readers. In the future, when more manufacturers go to higher frequency bands, the reading distances will increase and the size of tags and reader antennas will decrease.

As mentioned above, the electromagnetic field does not penetrate into electrically conducting materials in the UHF range. Because concrete walls always contain steel bars and other conducting materials, the wave will be reflected on the surface of the wall. This is why a line of sight is not always required to read an UHF-tag in a corridor or stair.

On the other hand, reflections will give rise to a phenomenon called interference. This means that the electromagnetic fields of the incoming and reflected waves are summed in every point of space where they exist together. The intensity and relative phase between the waves determine what the resultant will be. It can be a direct sum of both intensities, which will lead to a pronounced intensity. Or it can result to a zero field, if the waves are equal in intensity but in opposite phase. Because of this, it is very difficult to predict what the reading distance in a corridor or stair is without thorough measurements. In the following tests the antenna placement, orientation and power selection was not optimal in this respect, since it was not possible to tune the equipment with a large group of people before the actual tests.

2.3 Mathematical expressions for the evacuation flows

From the time series of counted persons we can take the slope of the count-time -curve, which represents the flow rate J [persons·s^{-1}] of doorways or stairs expressed as,

$$J = \frac{\Delta N}{\Delta t}, \tag{1}$$

where ΔN is number of evacuated people in a certain time interval Δt [s].

Specific flow J_s [persons·s^{-1}·m^{-1}] is the flow rate divided with the width W [m] of the doorway etc. written as,

$$J_s = \frac{\Delta N}{\Delta t \cdot W}. \tag{2}$$

The walking speed v on stairs can be calculated using the distances L [m] between the antennas at different floors measured using the walking line and the time Δt_{RFID} [s] it takes to descend between the antennas. Thus, the speed is,

$$v = \frac{L}{\Delta t_{RFID}}. \tag{3}$$

It is notable that the walking speed expressed by the Equation (3) is inclined walking speed that is the resultant of horizontal and vertical walking speeds.

Now the crowd density ρ_c [persons·m^{-2}] on stairs can be written as,

$$\rho_c = \frac{J}{v \cdot W} = \frac{\Delta N}{\Delta t} \cdot \frac{1}{v \cdot W}. \tag{4}$$

Here ρ_c is measured along the slanted direction of the stairs. To get the projection on a horizontal surface, ρ_c must be divided by cos(θ). where θ is the angle of slope for the stairs.

3. Evacuation from a public library

3.1 Building description

The Main Library of Helsinki University of Technology is a public library with a daytime staff of 30…50 and possibly several hundreds of library users. The main entrance and the staff entrance of the library are shown in Figure 3. A floor plan and the numbering of the library doors during the evacuation are shown in Figure 4. The visitors normally use doors 2 and 6. The staff also uses door 1. Door 3 is for transportation of goods and is rarely used. Doors 4, 5 and 7 are only used for evacuations.

When visiting the building, the visitors normally enter the main lobby from either door 2 or 6. From the lobby, they climb to the second floor through the two main stairways. From the second floor, the visitors may access the library collections and reading room in the first and underground floors through the two internal stairways. The access to the evacuation doors 4 and 5 is through the internal stairways. The widths of the doors and corresponding stairways are listed in Table 1.

Table 1. Widths of the library doors and stairways.

	Door(s) [m]	Stairway [m]		Door(s) [m]	Stairway [m]
Door 1	0.86		Door 4	0.86	
Door 2	3× 0.96		Door 5	0.86	1.20
Door 3	0.86	1.20	Door 6	3×0.96	

Figure 3. The Helsinki University of Technology (HUT) main library. The main entrance (door 2) on the left and staff entrance (door 1) on the right.

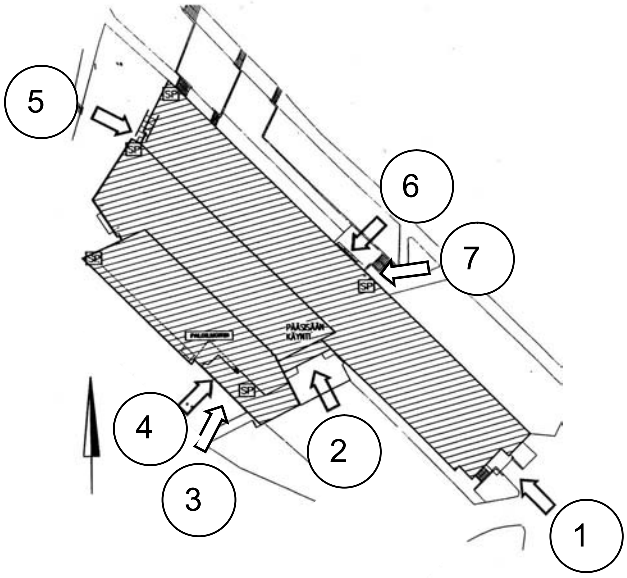

Figure 4. The numbering of the doors for HUT main library.

3.2 Planning and instrumentation

The evacuation was carried out as part of the safety training program of the library staff. The staff was informed that the evacuation would take place in the given day. The library visitors were notified on the evacuation exercise by printed notes on the entrance doors. Exact time was not specified, nor were the details of the evacuation.

It was anticipated that most staff members would exit through door 1 because that was the door they normally used. Therefore, two different RFID techniques and a stereo camera were used at door 1. A vicinity sensing reader ID ISC.LR200-A by FEIG ELECTRONIC GmbH working at 13.56 MHz frequency was used with a custom made antenna installed to the exit door. The remote sensing Deister reader working at UHF frequency was placed outside the door to a distance of approximately 3 meters. Before the evacuation, a group of 33 people of the library staff were equipped with two different types of RFID tags.

Immediately before the evacuation, researchers entered the building to make observations on crowd behaviour and outside the building to observe all doors. Video cameras were used to observe the evacuation from doors 1 and 4.

3.3 Results

3.3.1 Observations

The evacuation started at one o'clock in the afternoon. A smoke generator was put in operation in the lobby, thus preventing the use of doors 2 and 6. A fire alarm went off 37 seconds after the smoke generator was started, and evacuation began. The alarm signal was a loud bell sound. Soon after the alarm, the staff members that were part of the safety organization started to lead people towards the evacuation doors. In only few seconds after the alarm, the smoke started to flow up one of the main stairways. In 5 minutes 52 seconds after the fire alarm, all 189 people, that had been in the building, had evacuated.

After the fire alarm, the people in the second floor had to choose between three possible routes: main stairway and two evacuation doors through the internal stairways. The smoke filled the main stairway very soon after the alarm and made it impossible to use. In that situation, a great majority of people decided to evacuate through the stairway and door number 5, which was in the opposite end of the building to the 'fire'. During the evacuation, people clearly followed the majority of the crowd to the door 5, even though they had to wait some time the access to the stairway. The staff members tried to give instructions and distribute people evenly to the two available stairways but the many evacuees did not pay much attention to these instructions.

The alarm signal was so loud and clear, that we can assume all the people observed the fire at the moment of fire alarm. After the alarm, people started to collect their things, pack the bags and wear jackets. Some people did all that in just a few seconds, some spent almost two minutes. The premovement times, i.e. the time from alarm to the actual movement towards an exit, of 42 people were collected from the videos. The average premovement time was 36 s. The cumulative distribution of these times is shown in Figure 5, accompanied by the LMS-fitted Weibull and LogNormal distributions. The Weibull distribution is defined as

$$f(x;k,\lambda) = \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-(x/\lambda)^k} \tag{5}$$

and LogNormal distribution as

$$f(x;\mu,\sigma) = \frac{e^{-(\ln x-\mu)^2/\left(2\sigma^2\right)}}{x\sigma\sqrt{2\pi}} \tag{6}$$

The distribution parameters for the Weibull distribution are k = 1.8 and λ = 40, and for the LogNormal μ = 3.45 and σ = 0.57.

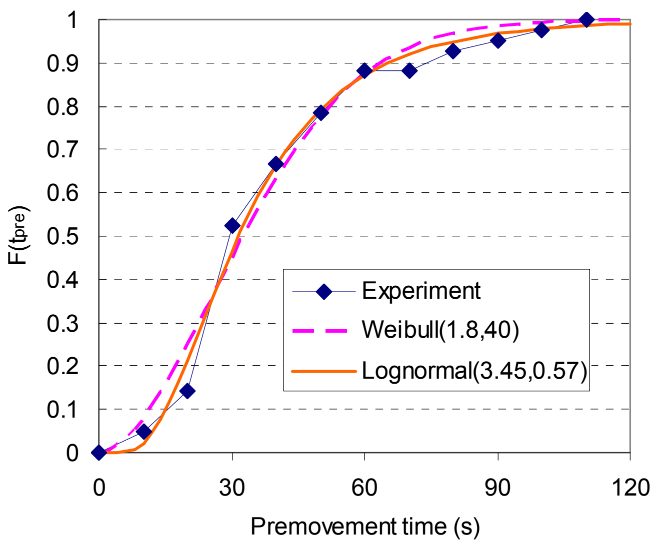

Figure 5. Distribution of observed premovement times (N = 42) in the public library and fitted Weibull and LogNormal distributions.

Our result for average premovement time was 36 s, which is much smaller than the value 73 s obtained by Gwynne et al. (2003) for the university students. Comparing our result to a larger amount of data, we can see that the average values for premovement time are in range of 19–83 s, see Table 2.

Table 2. Premovement times from different literature sources.

average	min	max	description	reference
00:19	00:00	03:12	evacuation from different building types	Purser & Bensilum (2001)
01:10	00:00	04:06	university staff	Gwynne *et al.* (2003)
01:13	00:08	03:20	university students	Gwynne *et al.* (2003)
00:44	00:16	01:31	hospital staff	Gwynne *et al.* (2003)
00:51	00:30	01:06	hospital patients	Gwynne *et al.* (2003)
00:30	00:19	00:54	furniture shop (Örebro IKEA) [1]	Frantzich (2001)
00:50	00:35	01:13	furniture shop (Örebro IKEA) [2]	Frantzich (2001)
00:50	00:51	00:57	furniture shop (Örebro IKEA) [3]	Frantzich (2001)
00:27	00:09	00:46	furniture shop (Västerås IKEA) [1]	Frantzich (2001)
00:51	00:40	01:07	furniture shop (Västerås IKEA) [2]	Frantzich (2001)
00:31	00:27	00:38	furniture shop (Västerås IKEA) [3]	Frantzich (2001)
00:26	00:15	00:50	furniture shop (Älmhult IKEA) [1]	Frantzich (2001)
01:02	00:45	01:40	furniture shop (Älmhult IKEA) [2]	Frantzich (2001)
01:23	00:35	02:10	furniture shop (Älmhult IKEA) [3]	Frantzich (2001)

[1] store side of the furniture shop
[2] restaurant side of the furniture shop
[3] near to cash desk

3.3.2 Escape monitoring

The flows of people out of the doors were monitored using stopwatches and video cameras. The video cameras were used for doors 1 and 4. The cumulative number of evacuated people as function of time was then calculated for each door. The results are shown in Figure 6. Most staff members used the door 1 and the most visitors used the door 5. The flow of people out of the door 5 was quite steady from about 70 s to 200 s from the alarm, and probably controlled by the width of the stairway and the doors leading to the stairway. The flow rate was found to be about 0.7 persons per second, which is 0.8 persons $s^{-1}m^{-1}$. However, the flow rate is based on the manual bookkeeping, and the uncertainty of the actual flow rate is quite high. Therefore, the flow rates presented here are only indicative.

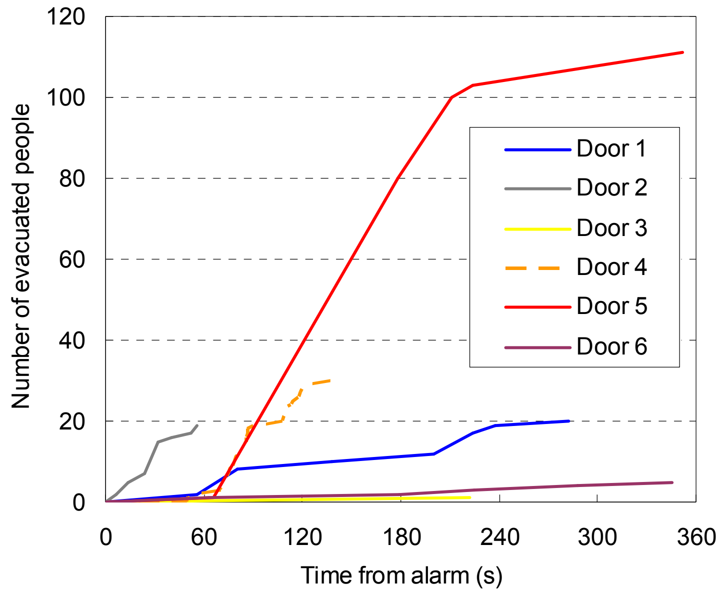

Figure 6. The cumulative number of evacuated people for the doors of public library.

The library evacuation was used for preliminary testing of the different technical monitoring techniques. Both inductive and UHF RFID antennas and stereo camera were installed at Door 1. A comparison of the video and technical observations revealed that

- According to the video tape, 20 people used to door for escape. 12 of these people had the RFID tags.
- The inductive RFID observed and identified 5 of 12.
- The UHF RFID observed and identified only 3 of 12.
- Only one person of 12 was observed by both systems.
- The stereo camera observed 22 people using the door.

The main reason for the low identification percentage was that the tags were placed close to the body or some other electrically conducting object, where the electromagnetic field ceased to exist. Test persons who were identified had the tags on their clothing or otherwise far away from their body. In the following tests, the tags were installed inside the ID badges and written instructions were delivered with the badges to each test person.

Based on these experiences, it was also concluded that more attention must be paid on the placement of the antennas. Now the antennas had to be placed in locations that were far from optimal taking into account the walking path of the evacuees. The preparation of the RFID tags and the analysis of the tag data were found laborious and complicated. The stereo camera seemed to be a reliable device for counting people, although it can not identify the evacuees.

4. Evacuation from a large office building

4.1 Building description

The second evacuation experiment was carried out in a large office building in Helsinki. The experiment differed from the library case mainly in terms of building geometry and number of the staff regularly working.

The building has 7 floors and 4 entrances from the street level. Normally, there are about 500 employees working in the building. The office building is illustrated in Figure 7, where the entrances are also shown. The door 1 is normally used as a main entrance of the building for staff and visitors. Doors 2 and 3 are used by the employees only, and lead from the street level to staircases, where the elevators and stairs can be used to access the upper floors. Door 4 is used as an exit in evacuation situations. There is an access from staircase 3 to staircase 2 through the first floor offices. This access is shown by the upward dashed arrow of staircase 3 in Figure 7.

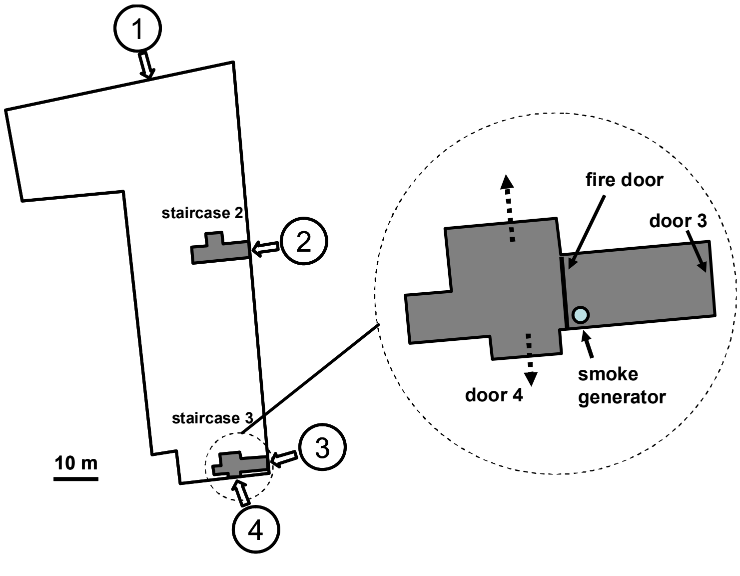

Figure 7. The geometry of large office building showing the 4 entrances. The gray areas present the staircases at the street level and the dashed arrows presents the exit routes from the staircase 3 in our experiment.

4.2 Planning and instrumentation

The evacuation was carried out as part of the safety training program of the building employees. The evacuation was planned by the fire researcher team, local safety organisation, and local fire brigade. The main idea of the exercise was to force the evacuees to use an escape route that was unusual and not used in daily basis. This was realized by blocking the entrances 1 and 3 (see Figure 7) with cold smoke.

Cold smoke generators (Figure 8) were operated manually by the safety organisation personnel. The generators were placed at the street level inside entrances 1 and 3. The smoke generator in staircase 3 was placed between the outer door (door 3) and a fire door, so that people could still descend safely using the stairs to the street level behind the fire door and then either walk inside the building to staircase 2 and the door 2 in, or use the door 4 for the evacuation, see Figure 7.

Figure 8. The white smoke plume arising from the cold smoke generator.

The observation focused the staircase 2. The staircase was equipped with six digital video (DV) cameras and five RFID antennas. For RFID, the FEIG reader with four antennas was assembled into the staircase. The antennas were placed on the entresol landing facing athwart down towards the descending test persons at a distance of approximately 2–3 meters, as shown in Figure 9. Antenna number 1 was between floors 6 and 5, number 2 between floors 5 and 4 and so on. The Deister reader (number 5) was placed at street level (floor 1) in front of the door 2. The reader was facing down approximately 1 meter above the evacuating people. Both readers were driven with the maximum 2 W power. Deister was controlled with a laptop PC and FEIG was acting as a data logger.

For RFID, four groups of people were chosen from the building. The groups were equipped with ID badges with colour code and a tag inside. Written instructions of correct attachment of the ID badge were given to each test person. Group 1 (red) received 23 tags, Group 2 (blue) 22, Group 3 (yellow) 16 and Group 4 (green) 20 tags. The red and blue groups were located on the 6th floor and the yellow and green groups on the 5th floor.

Figure 9. Left side: monitoring equipments between floor levels (RFID-antenna and DV-camera). Right side: snapshot of the DV-camera during the evacuation exercise, where also the (red) RFID-tags are shown. The RFID tag recognition region of the antenna was close to the first descending person in figure on the right side.

The other locations of observations were outside the other exit doors, as shown by Figure 10. In addition, researchers were making observations at the street level inside staircases 2, and 3, and in the lobby of the main door.

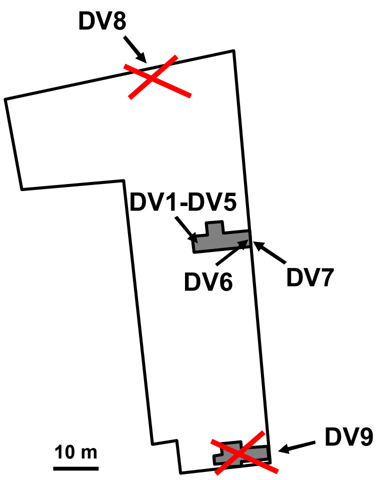

Figure 10. DV-camera locations in the large office evacuation exercise. The crossed exits were blocked with cold smoke.

4.3 Results

4.3.1 Observations of evacuation exercise

The evacuation exercise was held in November 2006. Before the evacuation, the employees were informed that the exercise would take place at the certain day. Information was printed out on the walls of the elevators.

Observers of the staircase 2 stayed at the street level, thus minimizing the disturbance of the human behaviour at the upper floors. The evacuation exercise was carried out in guidance of the building safety organisation. The members of the safety organisation wore yellow safety waistcoats for identification. The last few people evacuating the building were also members of the safety organisation.

The smoke generators were turned on simultaneously in staircases 1 and 3. It took about 2 min before the fire alarm went off, and the evacuation started. The first people came out from the staircase 2 in about 1 min from the alarm. Most of the people came out, as planned, through staircase 2. From doors 1 and 3, the first people came out in about 1 min, when smoke was not yet filling all the space. They all belonged to the safety organisation. The local fire brigade arrived to the main entrance and started the fire attack at 6 min 40 sec from the alarm.

The evacuation through staircase 2 was afterwards analyzed using the video recordings. Most of the people walked calmly and no rushing was observed. Queuing was observed, because some individuals decided to stop and give way for the flow descending from the upper floors. One big queue was once formed when a small group of people coming from the upper floors stopped for 60 s and allowed the flow from the office to enter the stairway.

4.3.2 Identification of evacuees using RFID

The percentage of tags identified during the test was much better than in the public library. Table 3 shows the number of tags delivered and observed in any of the five measurement points. As can be seen, almost all the tags were observed at least once.

Table 4 presents the percentage of tags observed on each floor compared to the total number of tags delivered. Four upper floors were measured with the same reading device. Differences between the floors are partly due to unexpected paths of the evacuees. The yellow Group 3 is a good example of this. They were expected to start from floor 5 like the green Group 4, but instead they seem to have passed by the whole staircase and appear only on floor 1. Most likely this kind of behaviour applies to all other groups as well to some extent. Group 3 is only included in total average.

Table 3. Number of tags delivered and identified in the large office building.

Group	Group 1	Group 2	Group 3	Group 4
Tags delivered	23	22	16	20
Tags observed	20	18	13	19
Percentage of identified tags	87.0	81.8	81.3	95.0

Another reason for the differences may be the velocity on a certain floor. On the upper floors 5 and 6 together with floor 3 the percentage of observations is smaller than in floors 4 and 1. When the road is blocked people tend to slow down and maybe turn around a few times. This gives the reader devices more time and opportunities to identify a specific tag even if people stand close to each other and block the line of sight to the reader. The reader antennas may also have been misaligned thus causing lower percentages at some floor.

The number of observations on each floor is compared to the total number of observations of a certain group in Table 5. The same tendency is shown as in Table 4. Both tables show that the degree of success is close to 60 %. The percentage of tags identified in all measurement point is shown in Table 6.

Table 4. Degree of success in indentifying tags on a specific floor. See text for expected reason for poor success on Group 3. Group 3 is only included in total average.

Floor	Group 1 %	Group 2 %	Group 3 %	Group 4 %	Average %
6	47.8	18.2	-	-	33.0
5	60.9	40.9	0.0	10.0	37.3
4	73.9	50.0	0.0	90.0	71.3
3	47.8	22.7	0.0	65.0	45.2
1	65.2	63.6	81.3	70.0	70.0
Average %	59.1	39.1	81.3	58.8	← 59.6

Table 5. Degree of success in indentifying tags on a specific floor. All percentage values are compared to the total number of observed tags in a group. Group 3 is only included in total average.

Floor	Group1 %	Group2 %	Group3 %	Group4 %	Average %
6	55.0	22.2	-	-	38.6
5	70.0	50.0	0.0	10.5	43.5
4	85.0	61.1	0.0	94.7	80.3
3	55.0	27.8	0.0	68.4	50.4
1	75.0	77.8	100.0	73.7	81.6
Average %	68.0	47.8	100.0	49.5	← 66.3

Table 6. Percentage of tags identified in every floor. Group 3 is not included in the average.

Group	Group 1 %	Group 2 %	Group 3 %	Group 4 %	Average %
Compared to tags delivered	26.1	13.6	0.0	10.0	16.6
Compared to tags identified	30.0	16.7	0.0	10.5	19.1

All tables show that there is a lot of variation between the groups also. This may be due to the differences between the briefings before the evacuation rehearsal in each group. Not necessarily all the evacuees have heard or read the instructions for using the ID badges. Clothing may also have an influence. Metallic zippers in the outerwear are made of electrically conducting material. Depending on how fast people leave the premises they may have different kind of clothing on.

4.3.3 Number of evacuated people and the crowd flow rates

The rate of evacuating people was counted using the MATLAB script described in section 2.1. The control line was determined from the DV-camera videos, so that every person that crossed the line was counted. The control line of the floor levels located just before the first tread going downwards (see Figure 11), and the control line of front door located at the doorway. The number of humans originating from a certain floor was counted by summing up the flows coming from the doorways on the left and right sides of the floor landing.

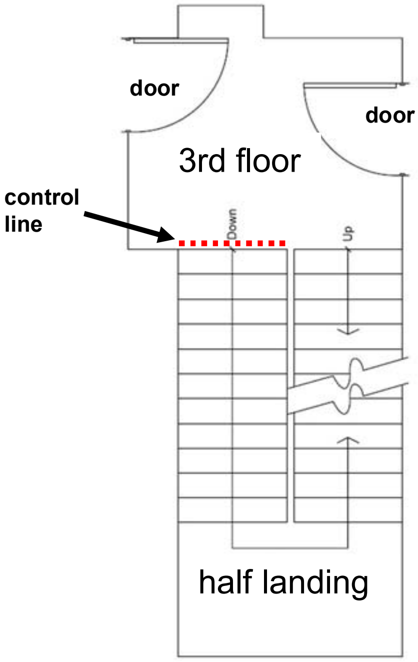

Figure 11. An example of counting the people in staircase 2. Number of people and the evacuation time together were recorded when one crosses the control line.

The number of evacuated people through staircase 2 is shown in Figure 12. Figure 12a shows the total flow of people down the stairs at each floor level. Figure 12b in turn shows the flow of people entering the stairway at each floor. Total number of evacuated people in 6 min period was 281. The linear parts of the curves show that the human flow was saturated due to the limiting width of the stairs and the front door. Figure 12b shows that the majority of the people came from the 4th and 1st floors. The number of people using the other doors was: 7 people from door 1 in 4 min, 3 people from door 3 in 50 s and 2 people from door 4 in 1 min 12.

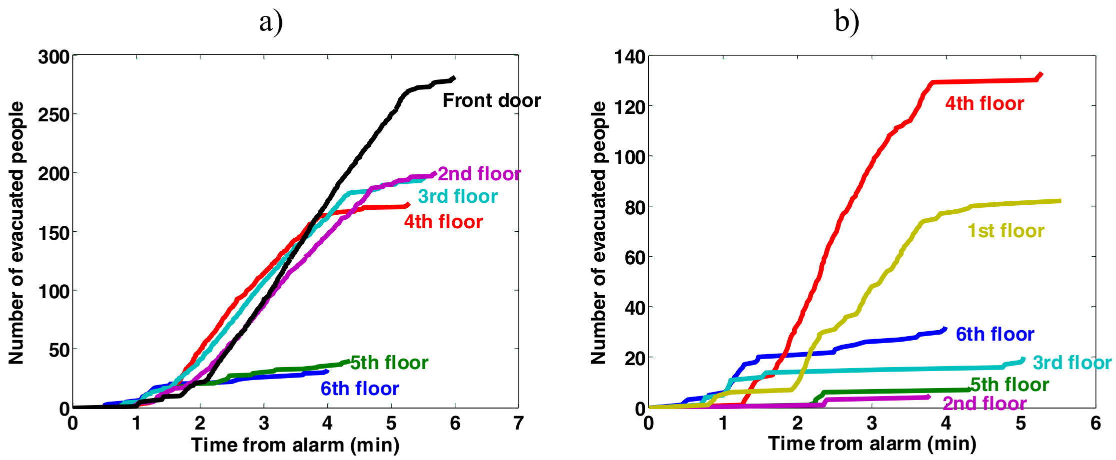

Figure 12. Number of the evacuated people from staircase. a) Accumulated starting from 6th floor and b) the number of persons per floor.

Table 7. The crowd flow rates in stairs and front door.

curve [a]	J (flow rate) [b] [persons·s^{-1}]	corridor/door width [m]	J_s (specific flow) [persons·s^{-1}·m^{-1}]
Front door [c]	1.35	1.07	1.26
2nd floor [d]	1.04	1.27	0.82
3rd floor [d]	1.05	1.27	0.83
4th floor [d]	1.02	1.27	0.80

[a] derived from Figure 12
[b] the linear part of the slope is calculated person values ranging from 50 to 150.
[c] flow rates on smooth floor
[d] flow rates on stairs

The computed flow rates are presented in Table 7. For a comparison, the SFPE Handbook (Nelson & Mowrer 2002) lists the maximum specific flow values in different conditions. For a doorway, they give 1.3 persons·s^{-1}·m^{-1}, which is in good agreement with our results. For stairs, the range is from 0.94 to 1.16 pers. ·s^{-1}·m^{-1} depending on the shape of the tread. Specific stair flow rates obtained in our study are slightly lower than the literature values. Possible reasons are the definition of the effective width of the stairs and the fact that in our study, the flow rate was affected by the merging flows from the side doors, especially in the first and fourth floors.

4.3.4 Walking speed and crowd flow density

RFID measurements were used to calculate the exact times spent by individual RFID tagged persons between floor levels. In order to calculate the walking speed, at least two time marks between two floors had to be found. Due to the error sources discussed in section 4.3.2, the number of RFID persons who left at least two time marks at different floors, and for whom the walking speeds were calculated, was relatively low, only 44 (63 %). The overall number of walking speed data points was 97, because for some persons, the whole walking history through the stairs was traced by the RFID system.

In the calculation of the crowd densities, the local flow rates, shown previously in Figure 12a, were used at same time as the first time mark to the RFID system was left. This local flow rate was assumed to last until the next RFID observation took place. The walking speed on stairs versus crowd density is presented in Figure 13. Strong dependence on the crowd density is found when the crowd density is smaller than 0.5 pers·m^{-2}. At higher densities, the walking speed decreases linearly. The difference between male and female data is not significant, as demonstrated in the right hand side figure showing the same data separately for male and female persons.

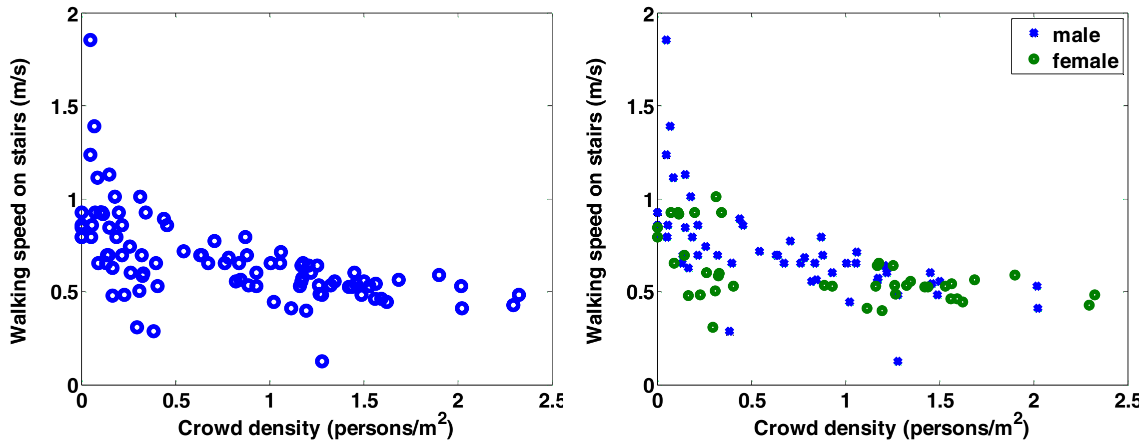

Figure 13. Walking speed on stairs as a function of crowd density. On the right side walking speeds are presented between male and female. Data points are derived from the traces of the RFID tagged persons in the staircase 2.

The overall cumulative distribution function for walking speeds on stairs is shown in Figure 14. A lognormal distribution function is fitted to the data points, showing a good correlation. The median of the fitted curve is 0.64 m/s and the 95 % fractile is 1.04 m/s. Comparison to the literature values shows that the current values are slightly lower than those measured by Fujiyama & Tyler (2004). They measured descending walking speed values[2] between 0.76–1.30 m/s by changing the stair angle from 24.6° to 30.6°, corresponding to a qualitative transformation from "normal descending" to "fast descending". In our experiment, the stair angle was about 27°. In the experiments by Fujiyama & Tyler (2004), the participants were walking alone and not in a crowd, which certainly have an increasing affect to walking speed values. The SFPE Handbook (Nelson & Mowrer 2002) suggests speeds between 0.85–1.05 m/s with varying tread shapes. Our result seems to be affected by the queuing effects.

4.3.5 Premovement time estimation

The RFID observations of evacuated people descending in staircase 2 are shown in Figure 15. These observations were used to estimate the distribution of premovement times in the office building. The times were measured by collecting the first recorded observations of each individual person by the RFID system at 5th and 6th floors, shown in Figure 15. The first recorded event takes place at 30 s and the last at 4 min. These are only the time values when a RFID tagged person appeared at the staircase, and the real premovement times are smaller. However, these results can be used to estimate the width of the premovement time distribution.

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[2] these values are the inclined walking speed values, based on the stair angles of Fujiyama & Tyler (2004).

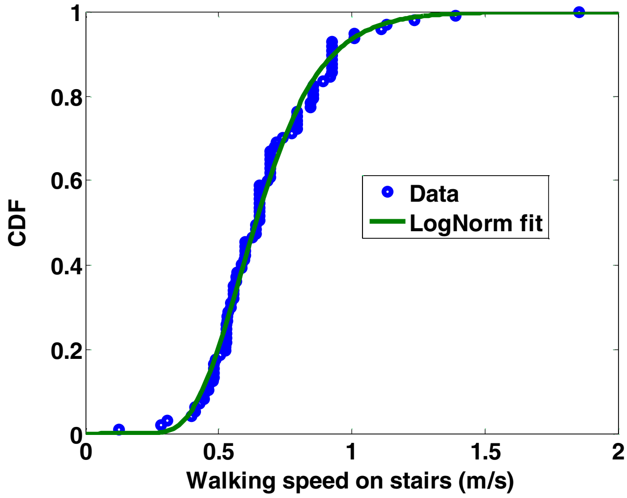

Figure 14. Cumulative distribution function of walking speeds on stairs and lognormal fit to data. The lognormal distribution function parameter values were μ = -0.4471 and σ = 0.2954. The last data point (1.85 m/s) belongs to a member of the safety organisation person who was running in empty staircase between floors 6 and 4 at the time of 4 min.

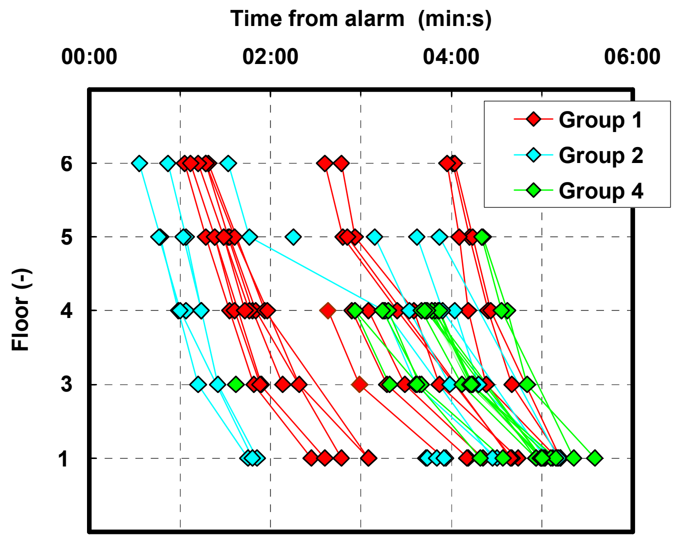

Figure 15. The recorded times of evacuated people descending in staircase 2. Each single line represents the recorded times of a single person. Note that the y-axis is not drawn linearly and that there was not RFID measurement in second floor. Group 1 and 2 worked at the 6th floor and the members of group 4 at the 5th floor.

4.3.6 Results of the inquiry form

Soon after the evacuation, the employees were asked to fill an inquiry form concerning the exercise. The form was on a web site, where the answers were recorded automatically to a database. The inquiry form consisted of 18 questions regarding the different aspects of the evacuation exercise and one open page for free comments. In free comments, where the number of respondents was 19, several people told they could not clearly hear the fire announcements during the exercise. Also some person would have wanted to have an exercise without any given briefing and information beforehand.

Some of the 18 specific questions and the answers for the staff are presented in Table 8. The key findings are

- The briefing and announcements were clearly noticed before the exercise.
- 67 % of respondents had no prior experience on evacuation exercises.
- Almost half of the respondents would have used the main door, the well-known route, to evacuate but in the exercise, doors 2 and 3 were mostly used. This was against our observations. The reason might be that the original alternatives of door selection were given as street addresses, not in a form of “door 1”, “door 2”. The respondents may have had difficulties to connect the address to a right exit door they used in exercise.
- About 70 persons used the route starting from the staircase 3 and finally ending to door 2 in staircase 2, due to the smoke in staircase 3. This movement could have been interpreted as a use of evacuation route of the staircase 3, which is closer to the street address. According to our book-keeping, the door 4 was only used by two persons during the whole exercise.
- Selection of the different route was mainly caused by smoke or safety organisation member guidance.
- Office staff felt slight congestion during evacuation in staircase, but it was not conceived as uncomfortable or anxious.

The information obtained from the inquiry form helps the office safety organisation and the staff itself to develop the evacuation procedure by revealing the strengths and weaknesses of the evacuation plan. For the researchers, information from the forms can be both quantitative and qualitative, demonstrating also some behavioural aspects of the evacuation event.

Table 8. Some of the questions delivered to the staff after the evacuation exercise of large office building (N = 90).

Did you know beforehand about the evacuation exercise?	
yes	100 %
no	0 %
Did you get briefing for the exercise?	
yes	94 %
no	6 %
Have you practised evacuation before?	
yes	33 %
no	67 %
How did you notice the "fire"?	
I noticed the smoke	6 %
I heard the alarm	90 %
Announcement given by the safety organisation	1 %
Announcement given by other personnel	3 %
I was not participated	0 %
Where did you locate, when you noticed the "fire"?	
In my own office	89 %
In coffee room	2 %
In conference facilities	4 %
In my workmates' room	2 %
In dining room	0 %
Other places (toilets, corridors etc.)	2 %
Which exit route you used? [a]	
Door 1	2 %
Door 2	47 %
Door 3	44 %
Other route	7 %
What was the first exit route you thought to use? [a]	
Door 1	45 %
Door 2	23 %
Door 3	21 %
Other route	3 %
I did not have time to think about it	8 %
How often you normally use the exit route you chose in exercise?	
Daily	17 %
Every week	20 %
Rarely	34 %
Never used before	29 %
What was the main reason for changing the exit route you first thought to use?	
The exit route was blocked (with smoke etc)	42 %
I followed the guidance from the safety organisation member	42 %
Because other personnel told me to use another route	4 %
I followed my workmates	10 %
Other reason	1 %
What did you do after noticing the fire alarm? You can choose many alternatives.	
I started immediately to walk towards the exit	36 %
I dressed up clothes before starting to evacuate	77 %
I first went to my office (for example searching my wallet or clothes)	8 %
I shut off or locked my computer	52 %
I finished the present work I was doing	5 %
We gathered a group of workmates and started to think what to do next	34 %
Did you close the door of the room you located at alarm?	
yes	21 %
no	22 %
I do not remember	3 %
I was not in a room with door	53 %

Did you face any rush at the floor you started to evacuate?	
no	44 %
slightly	39 %
yes, but the descending still continued	17 %
the rush was so dense that I felt uncomfortable	0 %
the rush was dense and anxious	0 %
Did you face any congestion at the stairs?	
no	17 %
slightly	48 %
yes, but the descending still continued	36 %
the crowd was so dense that I felt uncomfortable	0 %
the crowd was dense and anxious	0 %
Did you evacuate through the smoke?	
yes	7 %
no	93 %

[a] the original alternatives were not in form of "door 1, door 2, etc." but in form of name of the street address and, which might have confused the respondents.

5. Evacuation from a medium sized office building

5.1 Building description

The third experiment was organized in a medium sized office located in Helsinki. Normally, about 300 people work in the building. The building has 4 floors and 5 exits described in Figure 16. The door 5 is the main entrance to the building and the other 4 doors are used only for evacuation purposes. Doors 1–3 lead to an inner court of the building, from where the archway leads to the street. Door 4 leads straight to the archway.

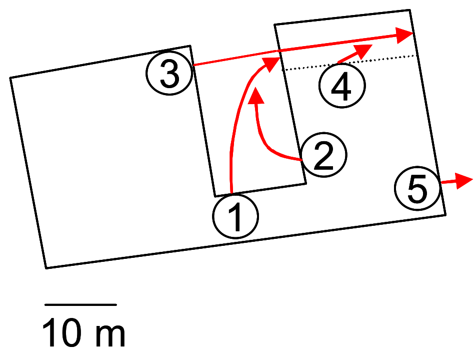

Figure 16. Medium sized office building having 5 evacuation routes illustrated with arrows.

5.2 Planning and instrumentation

The evacuation was carried out as part of the safety training program of the building employees. The evacuation was planned by the fire researcher team and the local safety organisation. The main idea of the exercise was to force the evacuees to use an escape route that was unusual and not used in daily basis. This was realized by blocking the internal stairway leading to main entrance (door 5) with cold smoke. It was anticipated that most people from upper floors would then use the route through staircase 1, corridor and Door 1.

The FEIG reader with four antennas was assembled into the internal staircase. The antennas were placed on the entresol landing facing down 1 meter above test persons. Antenna number 1 was between floors C4 and C3, number 2 between floors C3 and C2 and so on. The Deister reader (number 5) was placed on floor CP outside the staircase facing down approximately 1 meter above the test persons. Both readers were driven with the maximum 2 W power. Deister was controlled with a laptop PC and FEIG was acting as a data logger.

Test persons and tags were divided into four groups, which were marked with ID badges with colour code and a tag inside. Written instructions of proper attachment of the ID badge were delivered to each test person. Group 1 (red) received 29 tags, Group 2 (blue) 20, Group 3 (green) 30 and Group 4 (yellow) 23 tags. The red Group 1 was located on the C1 floor, the blue Group 2 on the C2 floor, the green Group 3 on the C3 floor and the yellow Group 4 on the C4 floor.

The DV-cameras were mainly used for recording the events of the internal corridor, as illustrated by Figure 17. Cameras were placed in both ends of the corridor and one camera to record the doorway of staircase 1. Outside the building, one camera per door was used (5 cameras in all) and one camera was placed in a car park at the basement. Cameras were not placed inside the staircase 1. The outside cameras were operated manually. Cameras inside the building were alone and they were started about 5 min before the alarm.

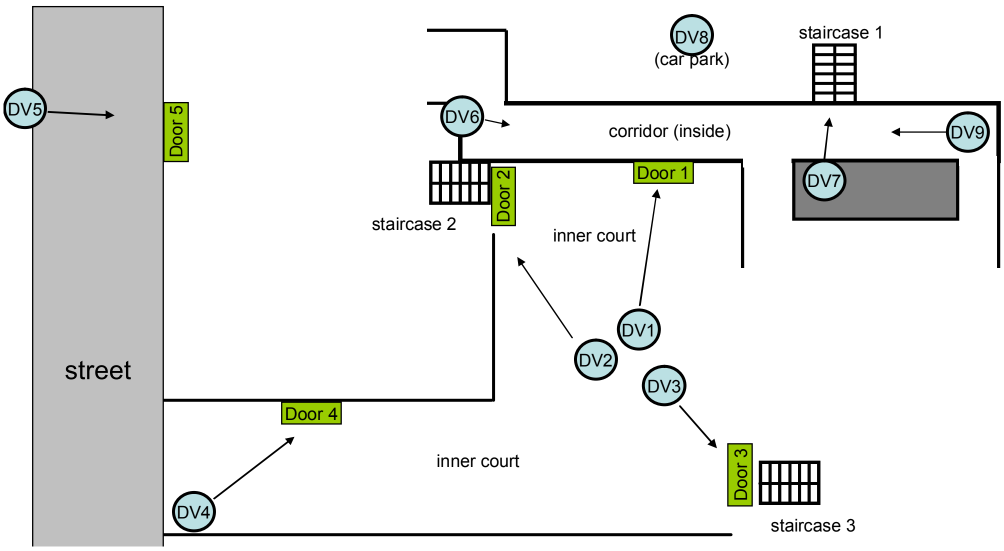

Figure 17. DV camera installations in medium sized office building. Drawing is not in scale.

5.3 Results

5.3.1 Observations during the exercise

A few days before the experiments, the office personnel were told the day when the evacuation would take place. The exact time of the exercise was not told. Afterwards, it was noticed that on the day evacuation exercise, the number of the workers was not close to its normal value estimated by the safety organisation group of the building. Thus, the number of evacuees in the experiment turned out to be much lower than planned.

The cold smoke generator operated only 2 min 30 s, and it was shut off, because it was assumed that the smoke would not spread to upper floors of the staircase 2. Despite this event, the smoke detector in the staircase 2 went off soon after shutting the smoke generator. One member of the safety organisation was standing in the stairway and preventing people from evacuating through the staircase 2.

Most of the people came out from the main door (door 5). At the time of the fire alarm, there was a visitor group coming in through the main door, but within only 10 s they decided to evacuate from the building. The door 3, which was assumed to be less familiar route the personnel, was used quite extensively because of the guidance of safety organisation. Only few people used the corridor and the staircase 1.

Within the staircase 1 it was observed that for most people, even for the safety organisation members, it was very difficult to leave the staircase at the right floor level, enter the corridor and then proceed to a right exit. Two small groups of 4 and 7 people were found follow the first person and descended all the way to the basement, where they noticed they are at wrong floor. After this they had to ascend one floor to get on the right route. These events took about 30 s for the first and 40 s for the second group.

5.3.2 Number of evacuees and estimations of the premovement time

The counting of the persons was done using the digital videos and the Evaccounter software. In Figure 18, the cumulative sums of evacuees for each door are shown. Most of the people came out from the doors 5 (the main door) and 3. The number of evacuees for the door 5 starts to increase immediately because the visitors came out at the same time as the fire alarm was given. Total number of the evacuated people was 139 and they came out within approximately 6 min.

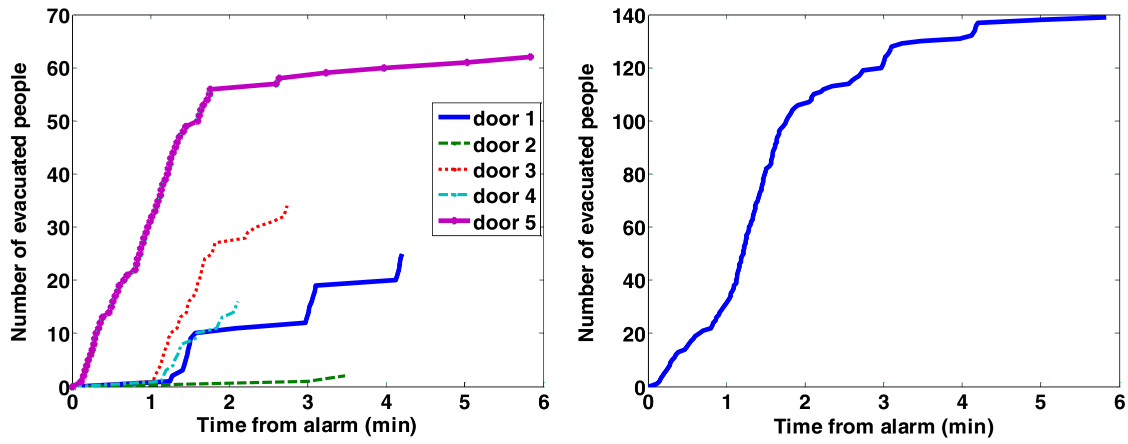

Figure 18. Left: number of evacuated people through each door. Right: the total number of evacuated people from the medium sized office building.

The flow rates determined from Figure 18 are 0.54 pers/s for door 3 and 0.58 pers/s for door 5. Both of the values are quite low compared to literature values and our former evacuation cases, thus revealing that the whole capacity of the exit routes was not used. Only about 30 people used door 1 and of those, only about 15 used also the staircase 1. Thus, crowd densities and walking speeds were not determined for this experiment.

Figure 19 shows the RFID recordings within the Staircase 1. The number of successful RFID recordings was only 12. The people entered the staircase 1–3 min from the alarm, which is a little bit faster than in the large office building.

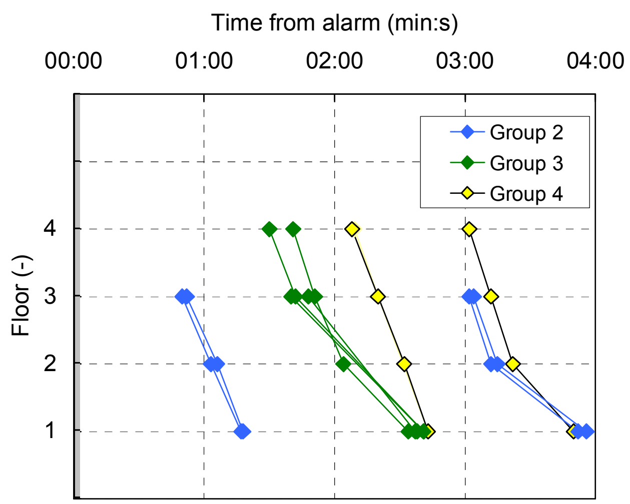

Figure 19. RFID recordings in Staircase 1 during the medium size office evacuation.

5.3.3 Identification of evacuees using RFID

A summary of the delivered and observed tags in the small office building evacuation is shown in Table 9. The percentage of tags identified was a little bit better than in the public library evacuation but much smaller than in the large office building. This is mostly due to the fact that many tests persons did not attend the test. The red Group 1 is an example of this. Thus, Group 1 is not included in the statistics below.

Table 10 presents the percentage of tags observed on each floor compared to the total number of tags delivered. The reason for the low percentages may be due to the lack of test persons. The percentages of identified persons per floor, compared to the total number of observations in a certain group are shown in Table 11. The real degree of successful identifications is somewhere between the values of Table 10 and Table 11. The percentage of tags identified in all measurement point is shown in Table 12. As in the two previous cases, there is a lot of variation between the groups. In this case, the variation is partly due to the small number of test persons.

Table 9. Number of tags delivered and identified in the small office building evacuation.

Group	Group 1	Group 2	Group 3	Group 4
Tags delivered	17	19	5	9
Tags observed	0	4	3	5
Tags identified (%)	0.0	21.1	60.0	55.6

Table 10. Degree of success in indentifying tags on a specific floor as a percentage of the total number of tags delivered to a group. Group 1 is not included in the average.

Floor	Group 1 %	Group 2 %	Group 3 %	Group 4 %	Average %
C4	-	-	-	-	-
C3	-	-	60.0	22.2	41.1
C2	-	21.1	60.0	44.4	41.8
C1	0.0	21.1	40.0	11.1	24.1
CP	0.0	21.1	60.0	55.6	45.5
Average %	0.0	21.1	55.5	33.3	← 36.5

Table 11. Degree of success in indentifying tags on a specific floor as a percentage of the total number of observed tags in a group. Group 1 is not included in the average.

Floor	Group1 %	Group2 %	Group3 %	Group4 %	Average %
C4	-	-	-	-	-
C3	-	-	100.0	40.0	70.0
C2	-	100.0	100.0	80.0	93.3
C1	0.0	100.0	66.6	20.0	62.2
CP	0.0	100.0	100.0	100.0	100.0
Average %	0.0	100.0	91.7	60.0	← 83.9

Table 12. Percentage of tags identified in every floor. Group 1 is not included in the average.

Group	Group1	Group2	Group3	Group4	Average
Compared to tags delivered	0.0	21.1	40.0	11.1	24.1
Compared to tags identified	0.0	100.0	66.6	20.0	62.2

5.3.4 Results of the inquiry form

Soon after the evacuation, the employees were asked to fill an inquiry form concerning the exercise. The form was on a web site, where the answers were recorded automatically to a database. The inquiry form consisted of 18 questions regarding the different aspects of the evacuation exercise but no space for free comments. The questions are summarized in Table 13.

We can see that 2/3 of the respondents have had some experience of evacuation before. The evacuation happened mostly by following other personnel and not by following the safety organisation members. The different doors were selected quite uniformly, and the main door was not highlighted, contrary to our observations. To avoid misunderstandings in door selecting questions, we now used the terms "door 1" and "door 2" accompanied by a map of the building with the door locations shown. The result may be affected by the small number of respondents. It is notable that over half of persons used an exit route that was not well-known for them.

Table 13. Some of the questions delivered to the staff after the evacuation exercise of medium sized office building (N = 48).

Did you know beforehand about the evacuation exercise?	
yes	88 %
no	13 %
Did you get briefing for the exercise?	
yes	58 %
no	42 %
Have you practised evacuation before?	
yes	67 %
no	33 %
How did you notice the "fire"?	
I noticed the smoke	6 %
I heard the alarm	88 %
Announcement given by the safety organisation	4 %
Announcement given by other personnel	0 %
I was not participated	2 %
Where did you locate, when you noticed the "fire"?	
In my own office	66 %
In coffee room	4 %
In conference facilities	19 %
In my workmates' room	0 %
In dining room	0 %
Other places (toilets, corridors etc.)	11 %
Which exit route you chose?	
Door 1	34 %
Door 2	4 %
Door 3	28 %
Door 4	11 %
Door 5	21 %
Other route	2 %
What was the first exit route you thought to use?	
Door 1	16 %
Door 2	20 %
Door 3	27 %
Door 4	7 %
Door 5	24 %
Other route	0 %
I did not have time to think about it	7 %
How often you normally use the exit route you chose in exercise?	
Daily	23 %
Every week	2 %
Rarely	19 %
Never used before	55 %
What was the main reason for changing the exit route you first thought to use?	
The exit route was blocked (with smoke etc)	19 %
I followed the guidance from the safety organisation member	0 %
Because other personnel told me to use another route	0 %
I followed my workmates	56 %
Other reason	25 %
What did you do after noticing the fire alarm? You can choose many alternatives.	
I started immediately to walk towards the exit	43 %
I dressed up clothes before starting to evacuate	60 %
I first went to my office (for example searching my wallet or clothes)	19 %
I shut off or locked my computer	15 %
I finished the present work I was doing	0 %

We gathered a group of workmates and started to think what to do next.	2 %
Did you close the door of the room you located at alarm?	
yes	30 %
no	32 %
I do not remember	17 %
I was not in a room with door	21 %
Did you face any congestation at the floor you started to evacuate?	
no	68 %
slightly	28 %
yes, but the descending still continued	4 %
the crowd was so dense that I felt uncomfortable	0 %
the crowd was dense and anxious	0 %
Did you face any rush at the stairs?	
no	52 %
slightly	39 %
yes, but the descending still continued	9 %
the rush was so dense that I felt uncomfortable	0 %
the rush was dense and anxious	0 %

6. Surveillance cameras as a source of evacuation data

6.1 Background

Even though the carefully planned and implemented fire drills and evacuation exercises may provide important information, there are some inherent problems as well. First, the information of the evacuation exercise is usually provided in advance, at least for some people, and the human behaviour may not be similar to the behaviour during a real evacuation situation. Second, it is quite expensive to organize the experiments. Despite the new technical monitoring techniques, the implementation is laborious and time consuming. If the experiment is performed in business spaces, the costs for the business as a loss of sale or loss of work time may be considerable. In shopping centres, the property owners may be afraid of the negative publicity.

On the other hand, real fires and false alarms do take place every now and then, and usually they cause the evacuation of the building. From the evacuee's viewpoint, these evacuations are real, and the behaviour depends on the estimated risk. The collection of data from these events might therefore be an effective means of research.

Many public buildings are nowadays equipped with surveillance cameras for security purposes. In shopping centres, for instance, the whole public space may be monitored by the security personnel. The modern surveillance camera systems have digital storage of the video material, and the video material from each camera can be viewed and processed afterwards. The utilization of such a video material was tested to find out the feasibility of surveillance cameras in research purposes.

6.2 Description of the evacuation scenario and video material

A large shopping centre in southern Finland had a false fire alarm in February 2007 due to a frozen sprinkler head. The shopping mall consists of tens of small and large shops in two floors. The four main entrances are connected to a main plaza in the middle of the building by walkways. The sliding doors of the entrances are equipped with latch doors on both sides that can be used to widen the doorway. The door widths are listed in Table 14.

At the moment of the alarm, there were more than 1000 customers in the building. When the frozen sprinkler alarmed, the security personnel decided to evacuate parts of the building. The whole building was not evacuated, because there were no other signs of a real fire, and because the weather outside was cold (about -10 °C).

Table 14. Widths of the entrance doors to the shopping centre.

Door	Sliding doors	Latch doors
Door A	2 × 1.61 m	2 x 3.47 m
Door B	1 × 1.61 m	1 x 3.47 m
Door C	1 × 1.61 m	1 x 3.47 m
Door D	2 × 1.61 m	2 x 3.47 m

The video recordings from four surveillance cameras were obtained. Three of the cameras were monitoring the entrances doors and one monitored a large entrance hall in front of the door. The quality of the video was relatively good, when compared to the surveillance cameras in general, but poor when compared to the quality of normal digital video cameras. The frame rate on the video is about 5 frames per second (normal consumer videos have 25 fps or higher) which means that a person walking at speed of 1.5 m/s travels 0.3 m during one frame. During the evacuation, the walking speeds are typically lower and the counting of people even at low frame rate becomes possible.

6.3 Results

6.3.1 General observations

Camera A

This camera was monitoring an entrance hall with two exits. The exits are not shows on the video, but one is able to observe the behaviour of the crowd. The main events observed are:

Time	
14:05:06	The video begins.
14:20:30	The first evacuees arrive to the hall.
14:21:40	The main crowd arrives to the hall.
14:23:30	A part of the crowd starts to move to a new direction, possibly to a new exit.
14:20:00	The rush starts to settle down.

Some general observations of the video are presented below:

- Many people have shopping trolleys, prams or wheelchairs. The effect of these people should be taken into account in simulations.
- There seems to be no pushing in the crowd. People keep on walking calmly.
- The decisions of other people seem to affect the evacuees. People follow their neighbours in the crowd even if they are not familiar with them. This can be observed on the event at 14:23:30.

Camera B

This camera was monitoring a corridor leading to an exit. The exit can also be seen on the film. There is an emergency exit next to the main exit. The main events are:

Time	
14:05:37	The video begins.
14:20:18	The first people evacuate through the exit. The emergency exit is not used.
14:21:22	Some people try to use the emergency exit but soon return to the main exit.
13:22:40	More people go to the emergency exit. Some of them exit through it and some return to the crowd.
14:23:52	A woman with a pram blocks the emergency exit.
14:25:22	The woman with the pram moves a little aside and some people exit through the emergency exit.
14:25:22	A door latch is opened and the exit becomes wider. The stream of people starts to move faster.
14:25:53	The rush in front of the exit settles down.

Camera C

Camera C was monitoring a corridor that is a mirror image of the corridor on Camera B. The emergency exit was almost completely blocked by a desk throughout the evacuation. The main events are:

Time	
14:05:06	The video begins.
14:14:20	The main crowd of evacuees arrive to the exit. The nearby emergency exit is almost completely blocked by a desk.

14:16:05	A door latch is opened and the exit becomes wider. The stream of people starts to move faster.
14:17:05	Another door latch is opened and the exit gets even wider.
14:18:12	The rush in front of the exit settles down.

As a general observation, the stream of people through the exit was very steady and jamming was not observed.

Camera D

This camera was monitoring a large entrance hall with two exits close to each other. Both of the exits can be seen on the video. The main events are:

Time	
14:05:13	The tape begins.
14:13:50	The evacuees arrive to the exits.
14:16:55	A door latch is opened at the right-hand exit, which accelerates the stream.
14:18:30	The rush at the exits settles down. Most people have evacuated.

As a general observation, it seems that the opening the latch at the right-hand side made that exit door more attractive to the evacuees than the exit door on the left.

6.3.2 Quantitative analysis of a surveillance camera video

The flow of people shown by Camera C was counted using the Evaccounter tool. The exact alarm time at the videos was not known (the videos do not have sound). In the analysis below, the alarm is assumed at time 14:14:00, when the first signs of unusual behaviour were observed. A snapshot from the videos is shown in Figure 20. People are heading towards the sliding door in the upper left hand side corner. The door has two sliding panes. On both sides of the door, there are doors with latches in the vertical frame. The left and right side doors were opened 128 and 185 s after the alarm, respectively. In the picture, the left side latch door is already open.

Figure 20. Snapshot of the surveillance camera during the shopping centre evacuation. The blue line shows the virtual counting line used in the analysis.

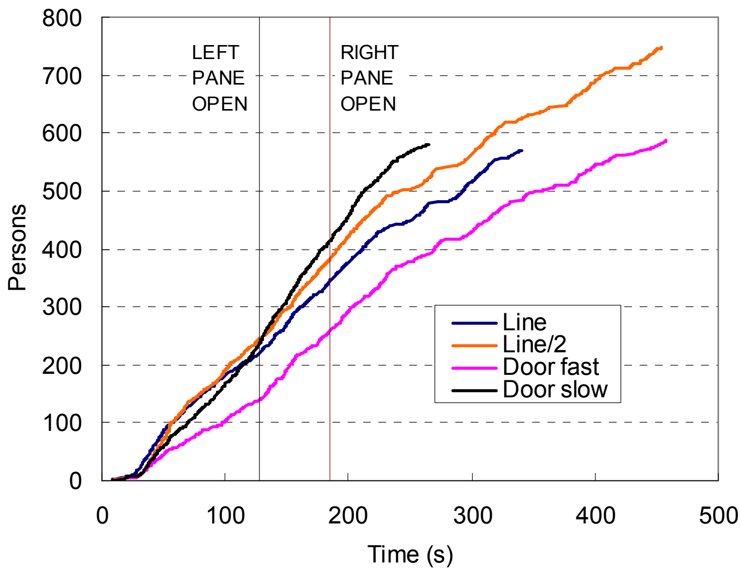

Figure 21. Flow out of door C.

The number of people evacuated through the door shown in Figure 20 was counted from the video. The results are shown in Figure 21. The people re-entering the building were neglected. The counting was first performed from the virtual door line. Two different playing speeds were used. At higher speed (*door fast*) the number of observed people was clearly lower than at slower speed (*door slow*). It was very difficult of observe all the people because the people blocked the visibility to the actual door line. This difficulty is demonstrated as large difference between the *door fast* and *door slow* results in Figure 21. The counting was also performed at a virtual line crossing the walkway, as illustrated by the blue line in Figure 20. To further increase the accuracy, the virtual line was divided in two parts, and the flows of people were counted for each part (*line/2*). As can be seen from Figure 21, almost 10 % more people were observed when the counting was performed as two pieces. Moreover, the number of people observed at the virtual line was clearly higher than at the door, when high play speed was used.

The flow rates corresponding to the four counting methods are shown in Figure 22. Some of the oscillations are probably caused by the numerical derivation process. When the highest peaks are omitted, we can say that the highest flow rate of 1.6 $(m\ s)^{-1}$ is found in the initial phase of the evacuation. After the opening of the second latch door, the flow rate goes down to 0.6 $(m\ s)^{-1}$.

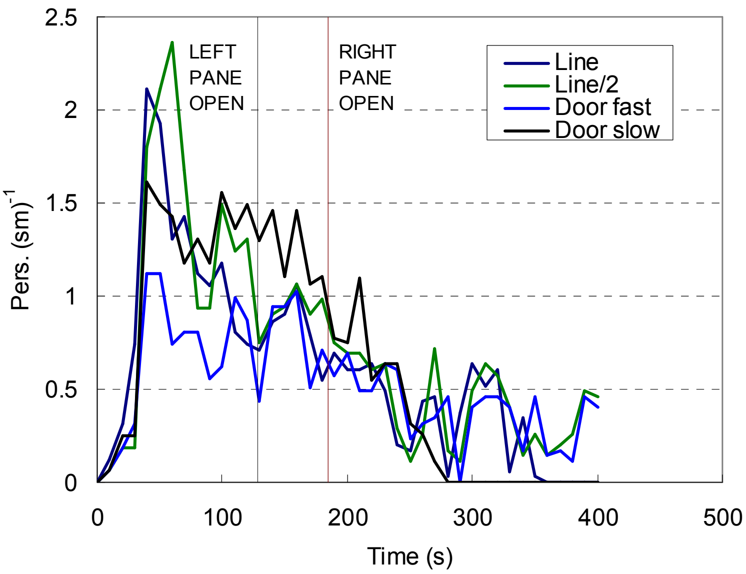

Figure 22. Flow rate out of the door C.

These results demonstrate that the surveillance cameras can be used to get detailed information on the evacuation in public spaces. However, the orientation of the cameras is crucial for the reliability of the counting. For good results, a perpendicular and unrestricted view on the evacuation path should be available. These conclusions apply only to the counting of people flows. Observation of reaction and premovement times was not possible from the available videos. In the future, the surveillance cameras may provide a valuable source of information on the realistic behaviour of people in fires on public places.

7. Discussion

7.1 Application of video cameras in evacuation tests

Video cameras are the primary measurement technique in evacuation tests. Whether the tests are performed in laboratory environment or in the field, they are simple to install and use and can provide versatile information. The entrance of the consumer level digital video cameras to the market has made it possible to use a large number of relatively good quality and easy to use cameras for evacuation observations. However, since this is not the primary use of these products, there are some issues that should be considered

- The cameras should be as light (and small) as possible to allow flexible mounting in the field measurements.

- The consumer level cameras may have automatic power saving features that turn off the power when the camera is idle for a certain time, and that can not be deactivated. The wireless remote control devices can be used to keep the cameras on before the beginning of the tests.

- The use of high capacity storage and possible "low speed" -mode allows recording times sufficiently long to start the recording even an hour before the actual test. However, the battery power may then become an issue.

The intended use of the video recordings should be kept in mind when planning for the camera positioning. For example, if the video is used to monitor a flow of people of the door, the camera should not be placed opposite the door, but rather on the side (angle of 45 ° or more from the wall normal) and above the head height.

Post processing of the videos is needed to get quantitative information on the things like premovement times and flow rates in the stairs or doors. Human interpretation is needed when the individual events (person moving or going through the door) are detected. During this work, a small survey on the automatic video analysis software for human detection was made but the results were not very good. A few companies were found that claim that their system can detect humans from the video images. However, some of the systems only worked on-line with the installed surveillance cameras. One company tested their system on the video material recorded during the public library evacuation, but the results were not promising. According to their own announcement, the reliable counting of people passing the virtual lines in the video image, the camera should be placed almost directly above the area being monitored. In the field tests, this is rarely possible.

7.2 Application of RFID in evacuation tests

The three tests where RFID techniques were applied showed promising results. Despite the small amount of testees and the uncertainty in the actual number of tags, it is quite evident that the percentage of identified tags will be better than 50% if proper alignment and measurement power of reader antennas is found by thorough experiments. This holds true even in crowded staircases.

Usually the best place to assemble an antenna is the ceiling. The antennas should be installed in a steep angle facing almost downwards and “uphill” towards the walking or descending persons. The tags should be placed horizontally as high as possible far away from the body of test persons. Tags designed to be used on metallic surfaces should be tested or special tags designed for person identification should be plotted.

The velocity of test persons is so small that the readers should be able to read all the desired tags. Usually the reading time of one tag is less than 0.01 seconds. Probably the most difficult thing to overcome is the difference in the size of people. Taller person in front of a shorter one is screening most of the electromagnetic field. Therefore, the use of more than one antenna on one measurement spot could help in this problem. When RFID-technique in person identification is becoming more common the prices of antennas will come down, since they are very simple in construction.

An integrated reader/antenna-design will help in places where the room ceiling is high. Long cable between the reader and a passive antenna will always deteriorate the reading distance. Reflections from different structures, steady or moving, are always a problem, but can be overcome with sweeping the power and angle of the reader beam.

Finally, these kinds of demonstrations/experiments do not tell much about the reliability of the technique itself, but the applicability of it for the given purpose.

7.3 Co-operation between the researchers and other organizations

If the evacuation tests are performed in the laboratory, the researchers have a full control on the test execution, type of information given to the evacuees and instrumentation. However, if the tests are performed in the field, the tests are usually performed in co-operation with the local safety organizations and possibly the authorities. In the three tests of this study, the tests were part of the safety training programs of the organizations.

The goals of the exercises defined at the different organizations may be different. For a successful implementation of the tests, it is extremely important to agree on the common goals that all the parties are willing to achieve. After that, it is easier to motivate and make the local organizers understand the need for extra work required. Scientific measurements always have a higher standard for documentation and preciseness than the evacuation training.

For the successful test execution, it is extremely important that the person leading the test or fire drill understands the needs of the scientific experiment. This person should be well informed on the “manuscript” of the test and the various measurements and their needs. If possible, the research organization should take the lead of the test.

8. Conclusions

The experimental techniques to observe the human behaviour during evacuation tests were studied in the evacuation of public library and two office buildings. The use of surveillance cameras was studied using the video material recorded during an evacuation of large shopping centre.

Video cameras are the primary technique of experimental observations in evacuations. The post-processing of the video material is still made by human interpretation, although the labour can be minimized by the use of simple software tools like the Evaccounter developed in this project. The commercial techniques for automatic human detection and counting were studied but without a success.

Promising results were achieved for the use of RFID as a means to make observations on the human movement in the evacuation. By the careful placement of both the antennas and the tags to be detected, a sufficient reliability for scientific measurements can be achieved. However, the results are very sensitive on the tag placement over or under the clothes, close to metal objects or behind parts of human bodies. The preparation and post-processing of the tag information is still relatively laborious because human interpretation of the results is needed in the analysis.

The results of the evacuation measurements provide information on the flow rates of people in the doors and stairways, effects of crowd density on the stair flow and distributions of premovement times. All these results can be used both directly as a basis of a building design or as a means to develop and validate the predictive capability of the evacuation simulation tools like FDS+Evac.

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